

**CONTROL LAW SYNTHESIS AND OPTIMIZATION SOFTWARE
FOR LARGE ORDER AEROSERVOELASTIC SYSTEMS**

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ABSTRACT

Motivation: A flexible aircraft or space structure with active control is typically modeled by a large-order state space system of equations in order to accurately represent the rigid and flexible body modes, unsteady aerodynamic forces, actuator dynamics and gust spectra. The control law of this multi-input/multi-output (MIMO) system is expected to satisfy multiple design requirements on the dynamic loads, responses, actuator deflection and rate limitations, as well as maintain certain stability margins, yet should be simple enough to be implemented on an onboard digital microprocessor. This paper describes a software package for performing an analog or digital control law synthesis for such a system, using optimal control theory and constrained optimization techniques.

Software Capabilities: The primary software capability is the optimization of the system by changing the control law design variables to improve stability and performance. A block diagram of the optimization scheme is shown in Fig. 1.

1) The optimization module minimizes a linear quadratic Gaussian (LQG) type cost function, while trying to satisfy a set of constraints on the conflicting design requirements such as design loads, responses and stability margins. Analytical expressions for the gradients of the cost function and the constraints, with respect to the control law design variables, are used for computation. This facilitates rapid convergence of the numerical optimization process. The designer can choose the structure of the control law and the design variables. This enables optimization of a classical control law as well as an estimator-based full or reduced order control law. Selected design responses are incorporated as inequality constraints instead of lumping them into the cost function. This feature is used to modify a control law to meet individual root-mean-square (RMS) response limitations and design requirements.

2) In order to improve the multiloop system stability robustness properties in the frequency domain, the minimum singular value of the return difference matrix at the plant input and output are as additional inequality constraints.

3) Other supporting capabilities include: (a) singular value analysis evaluation and plotting at the plant input and output; (b) linear quadratic optimal control law synthesis; (c) Kalman Filter design, LQG Loop transfer recovery; (d) pole-zero computation; (e) frequency response, Nyquist and Bode Plot; (f) root locus plot; (g) block diagonalization; (h) modal residualization and truncation; (i) transient response to deterministic and white noise input; (j) transfer of quadruple data to and from MATRIX-X and DIGIKON; (k) parameter search to stabilize an unstable control law, and (l) both interactive and batch mode execution using the Cyber NOS system.

Applications: The software has been used in the past for the following applications: (1) flutter suppression control law for the ARW-I wind tunnel wing model; (2) gust load alleviation control law for the ARW-II drone; (3) flutter suppression control law synthesis for ARW-II drone and the DC-10 Derivative wind tunnel wing model; (4) robust Digital gust load alleviation control law synthesis for ARW-II drone; and the (5) Active Flexible Wing (AFW) flutter suppression control law synthesis which is presently being carried out.

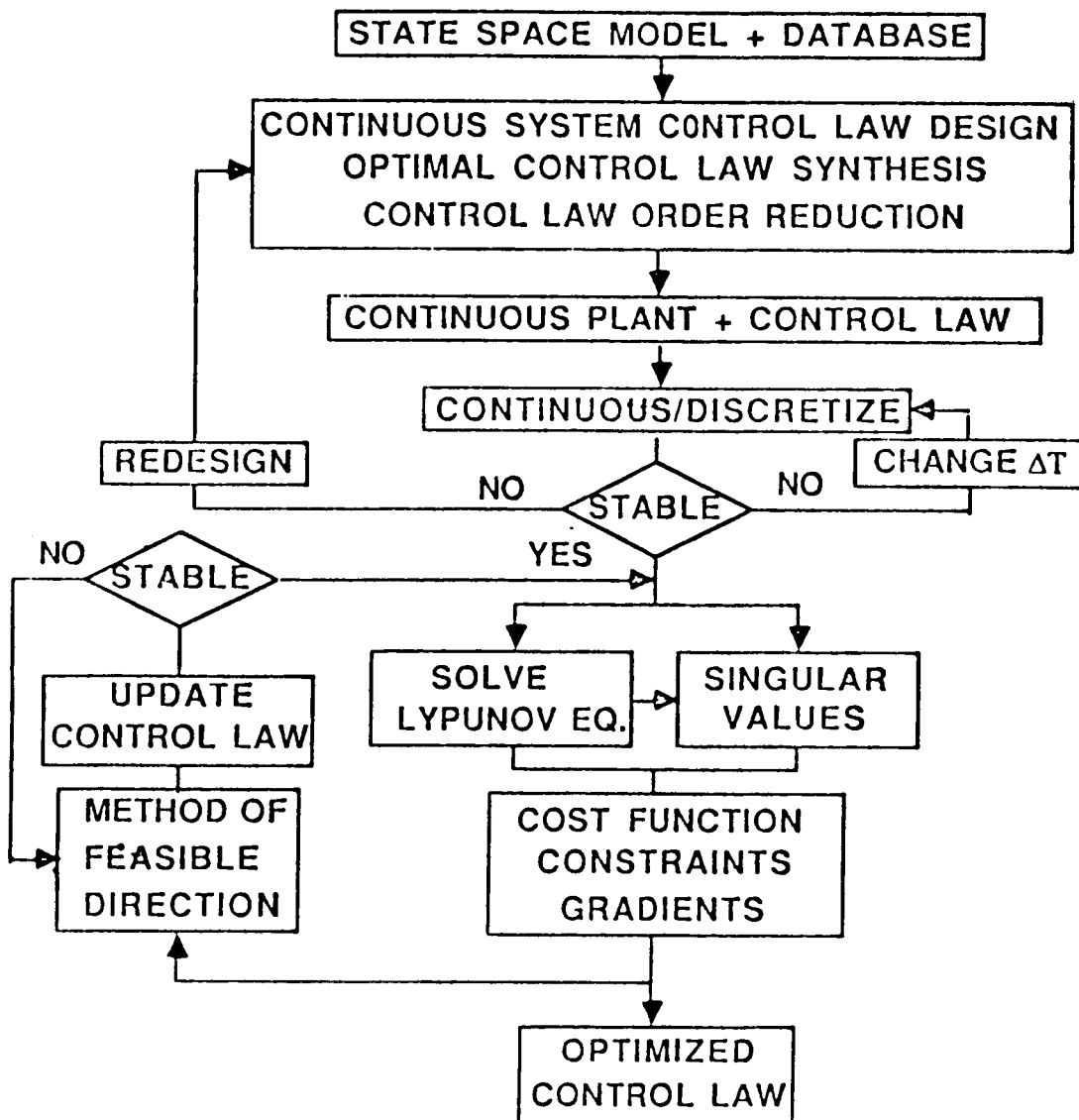


FIG. 1 Optimization scheme block diagram

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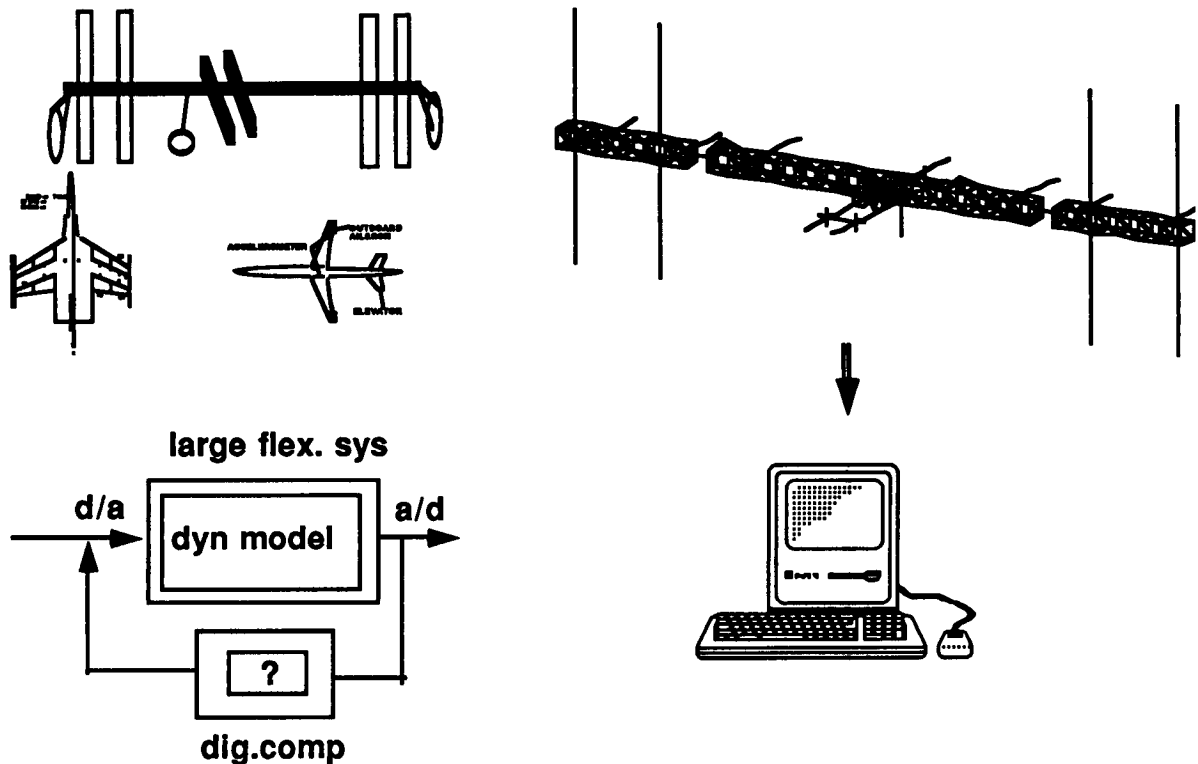
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Workshop on Computational Aspects in the
Control of Flexible Systems
Williamsburg, Virginia
July 12-14, 1988

Abstract

A flexible aircraft or space structure with active control is typically modeled by a large order state space system of equations in order to accurately represent the rigid body and flexible modes, unsteady aerodynamic forces, actuator dynamics and gust spectra. The control law of this multi-input multi-output (MIMO) system is expected to satisfy multiple design requirements on the dynamic loads, root mean square (RMS) responses, actuator deflection and rate limitations as well as maintain certain guaranteed stability margins, yet should be simple enough to be implementable on an onboard digital microprocessor. This paper describes an interactive software named DESIGN for analysis and synthesis of analog and digital control laws for such a system, using optimal control theory and constrained optimization techniques.



Overview

A multi-input multi-output aeroservoelastic system is typically represented by a large order state-space system of equations in order to accurately represent the rigid body and flexible modes, unsteady aerodynamic forces, actuator dynamics, gust spectra, antialiasing filters, computational delays etc. The active control law is expected to satisfy a set of conflicting design requirements on the performance and stability margins, yet should be simple enough to be implementable on an onboard digital microprocessors. This objective can be achieved using the synthesis software described in this paper. The methodology used are optimal control theory, order reduction techniques, unconstrained and constrained optimization with constraints on the design RMS responses and the minimum singular value of the return difference matrix at the plant input and output. Optimization can be performed for both continuous system and discrete systems. The methodology has been used to synthesize a) Analog and digital gust load alleviation control laws for a remotely controlled drone b) Analog and digital flutter suppression control laws for Active Flexible Wing (AFW) wind tunnel model. Other potential future applications include a) Rapid maneuver load control for AFW d) Vibration suppression for large space structure and control structure interaction study.

OVERVIEW

CONTROL LAW SYNTHESIS AND OPTIMIZATION SOFTWARE FOR FLEXIBLE STRUCTURE

DESIGN OBJECTIVES LOW ORDER ROBUST CONTROL LAW FOR A HIGH ORDER AEROSERVOELASTIC SYSTEM

METHODOLOGY OPTIMAL CONTROL THEORY CONTROL LAW ORDER REDUCTION NUMERICAL OPTIMIZATION

COST FUNCTION	LQG TYPE
CONSTRAINTS	RMS RESPONSES
	SINGULAR VALUES

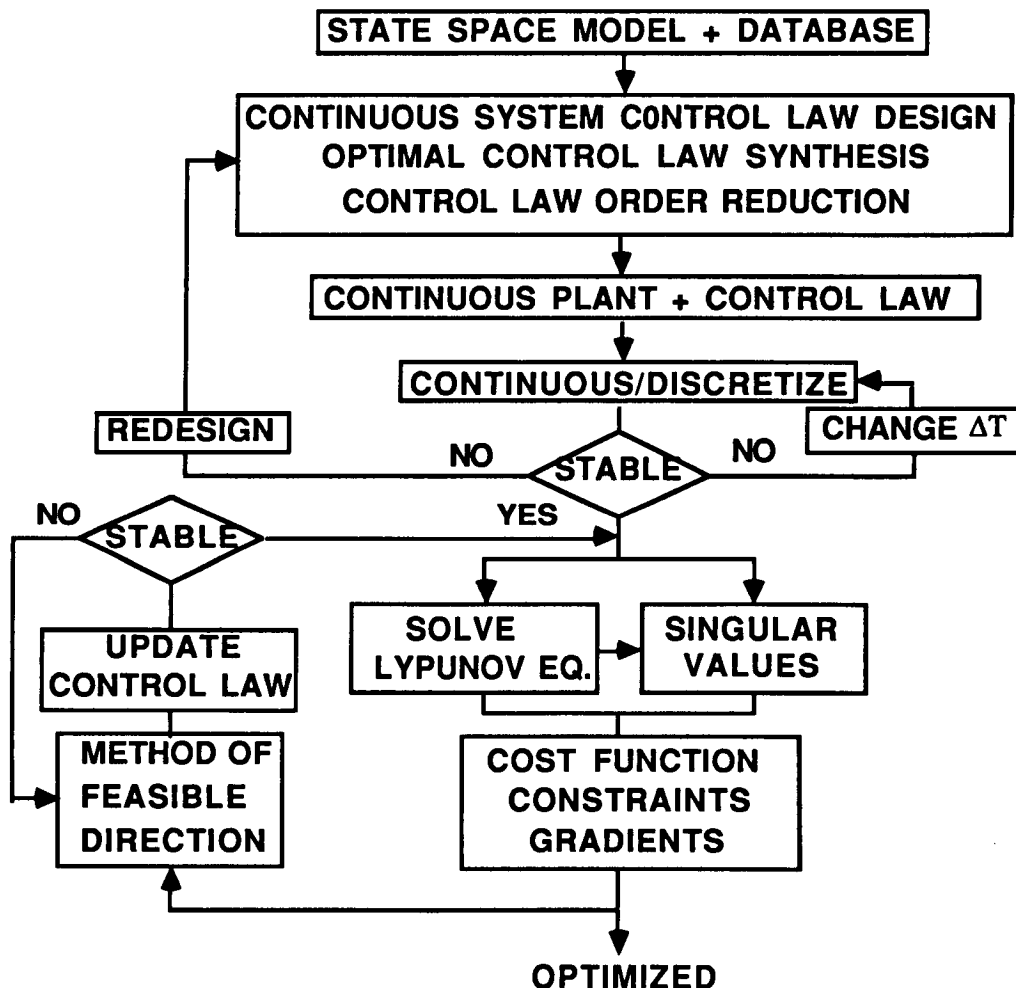
SYSTEMS CONTINUOUS DISCRETE

APPLICATIONS GUST LOAD ALLEVIATION OF A DRONE FLUTTER SUPPRESSION OF AFW MODEL RAPID MANEUVER LOAD CONTROL

Optimization Block Diagram

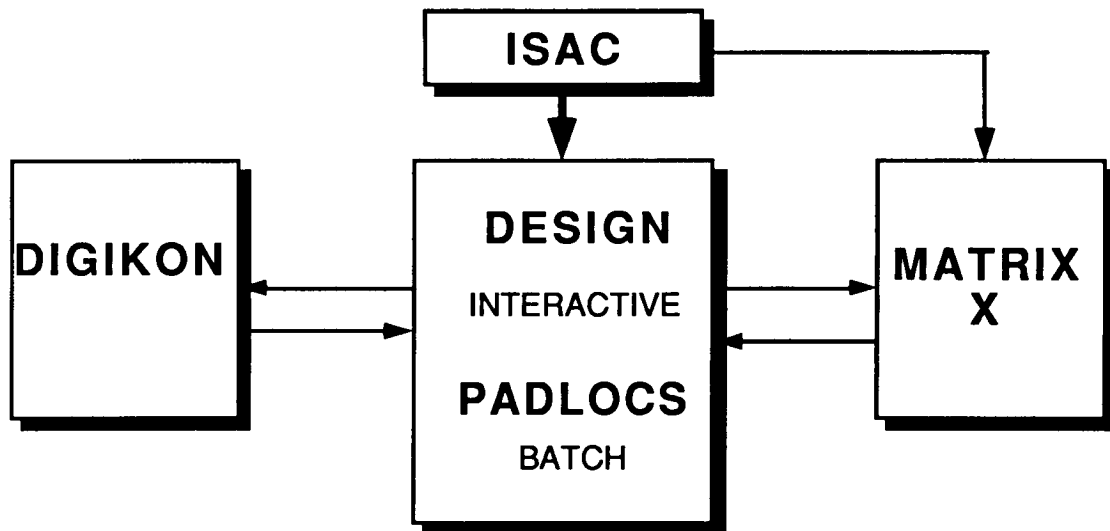
The optimization procedure minimizes a linear quadratic Gaussian (LQG) type cost function, while trying to satisfy a set of constraints on the conflicting design requirements such as dynamic loads, design RMS responses and singular value based stability margins at the plant input and output. The analytical expressions for the gradients of the cost function and the constraints, with respect to the control law design variables are used for computation. This facilitates rapid convergence of the optimization process. The designer can choose the structure of the control law and the design variables. This enables optimization of classical control law as well as an estimator based full or reduced order control law. Selected design responses are incorporated as inequality constraints instead of lumping them into the cost function. This feature is used to modify a control law to meet individual RMS response limitations and design requirements.

DISCRETE SYSTEM



Software Organization

The interactive software DESIGN is organized to interact with several well used softwares such as 1) ISAC (Interaction of Structure, Aerodynamics and Control) for receiving state-space quadruple data, 2) DIGIKON for discretization, interconnection, model generation, digital design, verification and graphics and 3) MATRIX-X for matrix manipulation, interconnection, quadruple data transfer, graphics and design verification. DESIGN can also be run in batch mode on the CYBER/NOS system for large order problems involving systems with more than 120 states with large number of design variables and constraints. This batch version was previously known as PADLOCS (Program for Analysis and Design of Linear Optimal Control Systems).

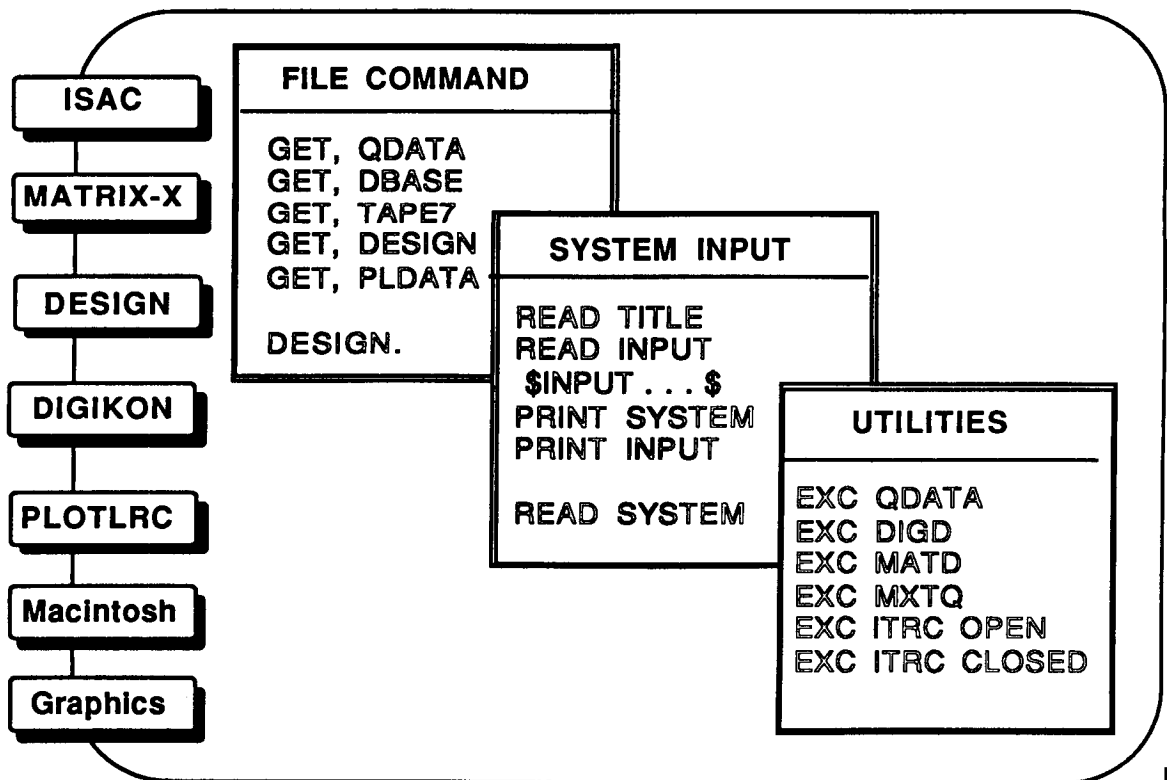


Basic Command Summary

The quadruple data is generated and stored in a sequential binary file called QDATA. The design starts with the file command

```
GET, QDATA.  
GET, DESIGN.  
DESIGN.
```

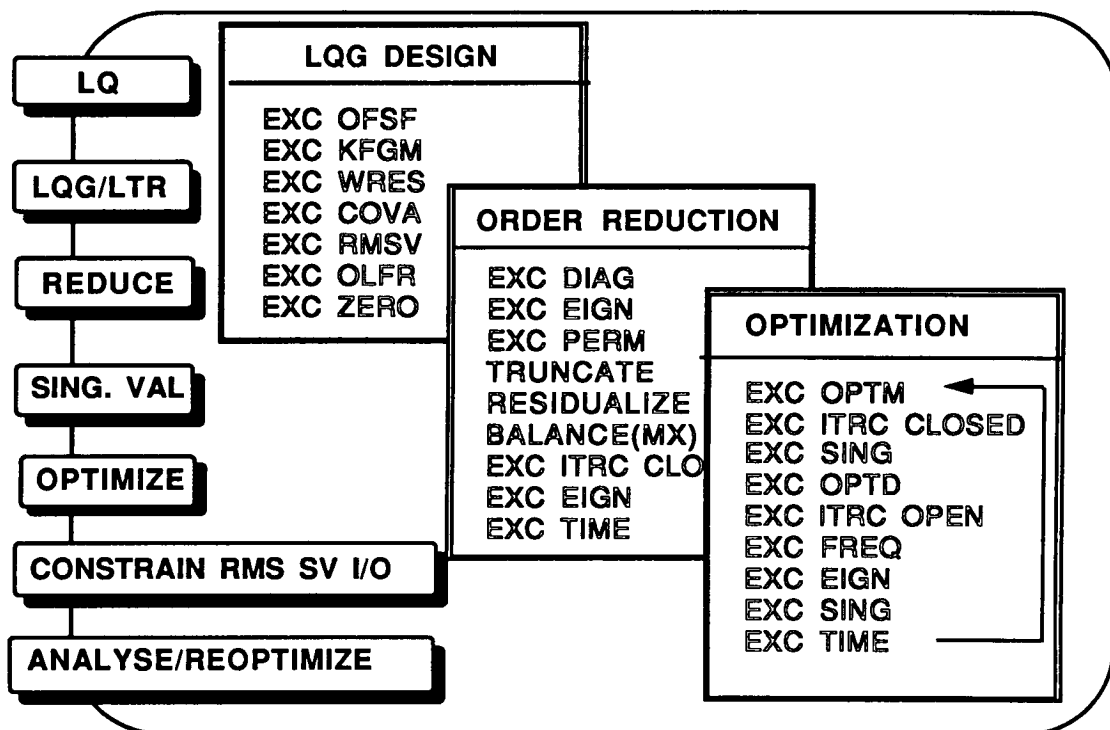
The random access files DBASE, and sequential file PLDATA are used to transport quadruple data to and from DIGIKON and MATRIX-X, while random access file TAPE7 is used to transfer data from ISAC.using the UTILITY commands. The system parameter and quadruple data are read by the SYSTEM INPUT commands as shown in the figure above. The primary capability of this software is the optimization of the system by changing the control law design variables to improve the stability robustness and performance requirements. The supporting capabilities include a) Linear quadratic optimal control law synthesis; b) Kalman filter design, linear quadratic Gaussian design (LQG) and loop transfer recovery (LTR); c) Singular value analysis , evaluation and plotting at the plant input and output; d) Pole-zero computation; e) Open and closed loop frequency response, Nyquist and Bode plot, and loop breaking test; f) Root locus plot g) Block diagonal transformation; h) Modal residualization and truncation; i) Transient response to deterministic and white noise input; etc.



Basic Design Commands

The basic design commands are shown in the figure above. For systems with known stable control laws the optimization procedure can be executed directly using the command EXC OPTM for continuous systems and EXC OPTD for discrete systems. For MIMO systems with no known initial stabilizing control laws, first an Linear Quadratic Gaussian (LQG/LTR) design is performed to obtain a full order robust control law using a set of LQG design commands. The order of the control law is then reduced by truncation, residualization or balanced realization method using DESIGN, DIGIKON or MATRIX-X. The singular value analysis and block diagonal transformation procedure is very helpful in the reduction process. Since this reduced order control law is not optimal and may not satisfy the design requirements, constrained optimization procedure is used to update the reduced order control law. Constraints can be imposed on the design RMS responses and minimum singular values at the plant input and output.

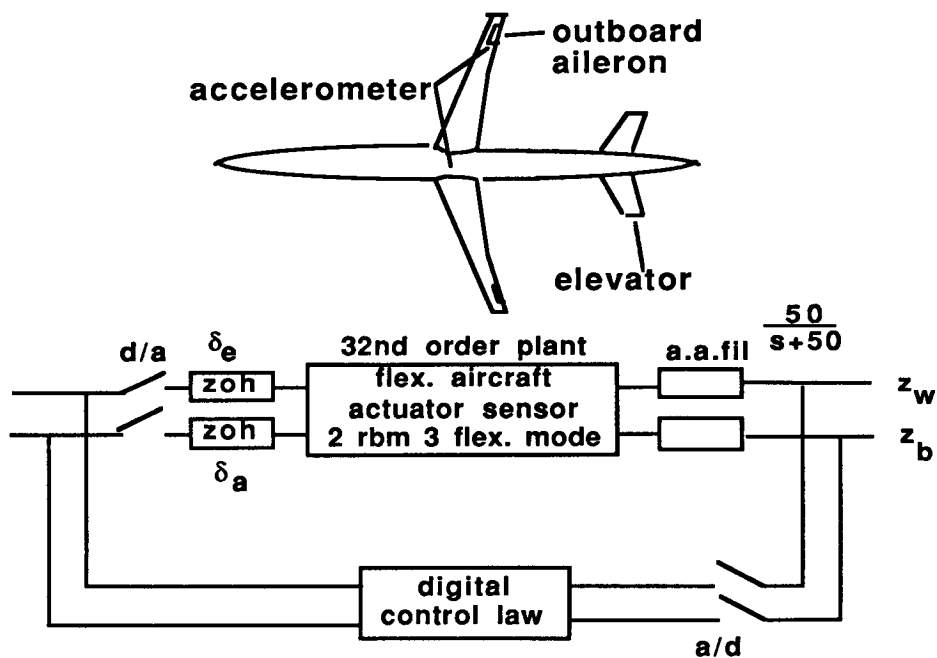
BASIC DESIGN COMMANDS



Gust Load Alleviation of A Flexible Drone

The synthesis procedure was applied to the gust load alleviation problem of a flexible drone. The basic control scheme is shown in the figure. In longitudinal motion, the symmetric elevator and outboard aileron deflections are used as the two control inputs. The accelerometer sensors at the outboard aileron and on the fuselage near the center of gravity are used as two measurement outputs. The output signals are filtered through first order antialiasing filters $50/(s+50)$ before digitization at 100 Hz. The two input two output system was modeled by a 32nd order system flying symmetrically through a Dryden gust.

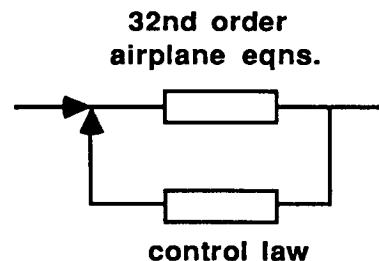
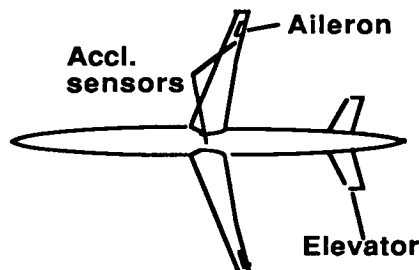
GUST LOAD ALLEVIATION OF FLEXIBLE DRONE



Gust Load Alleviation Design Requirements

The objective is to obtain a low order robust digital GLA control law which would reduce the open loop root-mean-square values of the wing root bending moment and shear by 50% without increasing the wing outboard bending moment and torsion. The control law should maintain certain guaranteed stability margins based on minimum singular value of 0.6 at both the plant input and output. The control surface deflections and rates should be within the allowable limits. First a full order LQG control law is synthesized to satisfy the design requirements. This 32nd order control law is then reduced to a second order control law and then discretized. This control law does not satisfy the design requirements. After unconstrained optimization most of the requirements are satisfied except the wing outboard bending moment and the singular values. Using constraints on the RMS wing loads and on the minimum singular values of the return difference matrix at the plant input and output, the control law parameters are reoptimized (Ref.1,2).

GUST LOAD ALLEVIATION DESIGN REQUIREMENTS

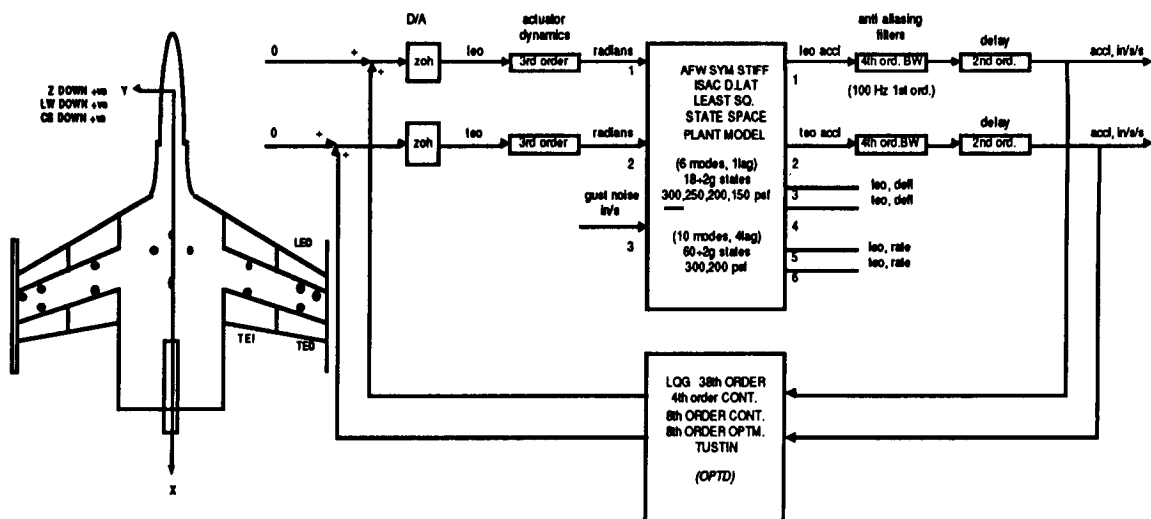


Physical quantities	Design objectives	How we do it
Root bending moment	50% reduction	1. LQG design 2. Control law order reduction 3. Discretize 4. Optimization 5. Apply constraints a) on rms loads b) on singular val.
Root shear	50% reduction	
Outboard bending mom.	No increase	
Outboard torsion	No increase	
Elevator deflection	Within max limit	
Elevator rate	Within max limit	
Aileron deflection	Within max limit	
Aileron rate	Within max limit	

Symmetric Flutter Suppression System

The software has been used in the past for the following applications: a) Robust flutter suppression control law synthesis for ARW-I wind tunnel wing model; b) Flutter suppression control law synthesis for ARW-II drone and DC-10 derivative wind tunnel wing model and c) s plane summation of forces load model (Ref. 3). A brief survey of the research activities is presented in Ref.4. Digital robust control law synthesis for the Active Flexible Wing (AFW) wind tunnel model is presently being carried out in collaboration with Rockwell International. The basic block diagram for a two input two output symmetric flutter suppression system is shown in the figure for a sting mounted model using leading edge outboard (LEO) and trailing edge outboard (TEO) symmetric actuators and colocated accelerometer sensors. The sampling rate is 200Hz. The design takes into account the effects of actuator dynamics, 4th order 100Hz Butterworth filters and one cycle computational delay at each channel. Full order and reduced order analog and discrete robust control laws were synthesized based on an approximate 38th order system at 300 psf design dynamic pressure. The discrete 8th order control law was able to stabilize the system over the range 300 to 150 psf. The more detailed 80th order model was also stable at 300 and 200 psf. Starting with these preliminary control laws detailed analysis will be carried out using the discrete system optimization procedure EXC OPTD.

SYMMETRIC FLUTTER SUPPRESSION SYSTEM



CONCLUDING REMARKS

- Software Improvement

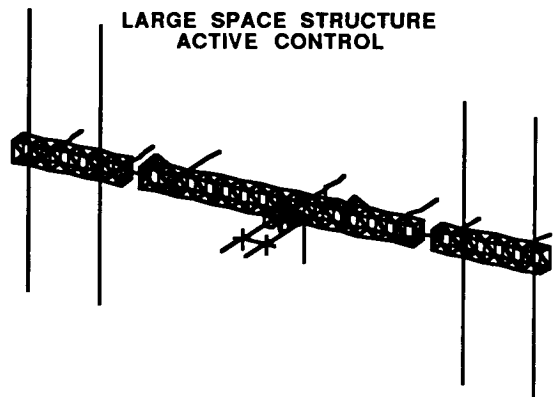
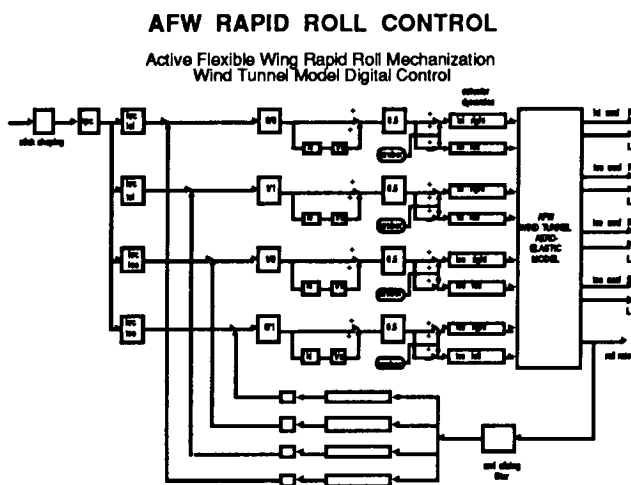
1. Direct time response constraints
2. New reduction techniques
3. H-infinity design
4. Additional derivative/sensitivity capabilities
5. User help and online documentation

- Portability improvement

1. Microvax
2. NOS VE

- **Future Applications**

1. AFW rapid roll maneuver
2. Large space structure-control interaction



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4. Abel, I. and Noll, T.E., Research and Applications in Aeroservoelasticity at the NASA Langley Research Center," 16th ICAS Congress, Jerusalem, Israel, August, 1988.